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Bidirectional Converter for On-Board Battery Charging in Plug-In Hybrid Electric Vehicles Using Reptile Search Optimization (RSO)

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KEYWORDS

Electric vehicle, Battery, Bidirectional converter, Inverter, Motor winding, RSO algorithm.

ABSTRACT

A novel hybrid control strategy for a bidirectional DC-DC converter used in on-board battery charging systems of Plug-In Hybrid Electric Vehicles (PHEVs). The proposed method utilizes the Reptile Search Optimization (RSO) algorithm to enhance control performance by dynamically adjusting gate signals to manage charging and discharging modes efficiently. The hybrid control scheme integrates both rule-based logic and intelligent decision-making to ensure robust energy flow management between the battery and the vehicle's DC bus. RSO is utilized to minimize tracking errors and optimize the switching pattern to improve charge efficiency, battery lifespan, and the overall system. The converter operates in buck mode during charging from the grid or renewable sources, and in boost mode during battery discharge to support vehicle load. Simulation results demonstrate the effectiveness of the proposed control technique in maintaining desired State of Charge (SOC) levels, reducing power losses, and ensuring seamless transition between operating modes. Comparative analysis against conventional PSO-based and rule-based controllers confirms the superiority of the RSO-based approach in terms of convergence speed and control accuracy. This research contributes to the development of more reliable and energy-efficient PHEV charging systems using advanced bio-inspired optimization techniques.

1. INTRODUCTION

Plug-in Hybrid Electric Vehicles (PHEVs) are emerging as a highly practical solution for sustainable transportation, as they combine the benefits of both internal combustion engines and electric propulsion systems [1] [2]. By utilizing a hybrid energy system, PHEVs allow for longer driving ranges, reduced fuel consumption, and lower emissions compared to conventional vehicles. A key subsystem in the overall PHEV architecture is the On-Board Charger (OBC), which enables energy transfer from the grid to the vehicle battery without requiring external infrastructure [3-4]. As demand increases for fast, efficient, and compact charging systems, researchers are focusing on enhancing the performance of OBC units while meeting space, weight, and cost constraints typical of automotive applications. Among the various components in OBCs, the bidirectional DC–DC converter plays a crucial role by enabling both grid-to-vehicle (G2V) and vehicle-to-grid (V2G) operations [5-6]. This bidirectionally not only supports conventional charging but also allows the vehicle to act as a distributed energy source for the grid during demand peaks. To further reduce component count and size, recent topologies have adopted the use of motor windings as passive inductors and integrated traction inverters as rectification units. Although these innovations help reduce weight and cost, they pose new challenges in terms of control, such as managing power flow, reducing current ripples, and ensuring battery protection during charging and discharging processes. To address these control complexities, various intelligent techniques have been proposed in recent studies. Conventional controllers like Proportional-Integral (PI) have been enhanced with intelligent approaches such as Particle Swarm Optimization (PSO), Neural Networks (NN), and their hybrids like ANN–PSO or ANN–IPSO. These algorithms provide improved dynamic response, better disturbance rejection, and higher efficiency. For example, an author Anjinappa et al. proposed an NN–IPSO-based control strategy for an isolated bidirectional converter. Their approach demonstrated improved Total Harmonic Distortion (THD), reduced power loss, and increased efficiency compared to conventional converters, making it a promising direction for advanced charger control.

To overcome these challenges, this paper proposes a novel control approach based on the RSO algorithm. RSO is a recent bio-inspired algorithm that mimics the intelligent hunting behavior of reptiles, offering a better balance between exploration and exploitation during the optimization process. The proposed method eliminates the need for neural network dependency while retaining strong convergence performance and accuracy. By integrating RSO into the control loop of the bidirectional DC–DC converter, this approach enables smoother energy flow control, reduced THD, and higher efficiency in both charging and discharging operations. MATLAB/Simulink simulation results demonstrate that RSO outperforms IPSO in convergence speed, SOC regulation, and power quality, making it a robust and scalable solution for future PHEV on-board charging systems. The remainder of this paper is organized as follows: Section II presents the detailed system design, including the overall architecture and converter configuration. Section III discusses the control strategy adopted for managing bidirectional power flow and maintaining system stability. Section IV introduces the proposed RSO algorithm-based control scheme and its integration into the converter topology. Section V provides simulation results and comparative performance analysis between RSO and existing IPSO-based methods using MATLAB/Simulink. Finally, Section VI concludes the paper by summarizing the key contributions and highlighting the future scope of this research.

2. SYSTEM DESIGNING

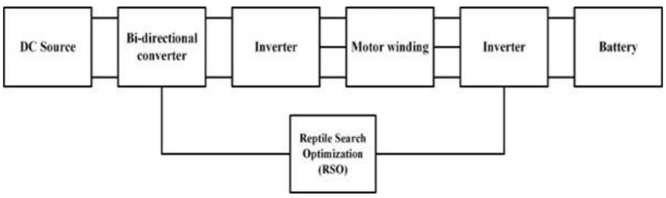


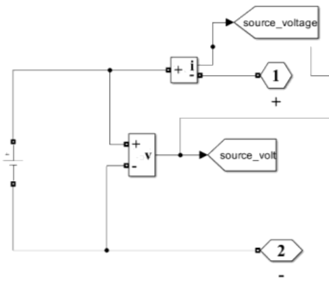
Figure.1 Block diagram of the system

The proposed bidirectional converter-based on-board charging system for PHEVs is designed to ensure intelligent energy flow between the DC power source, the electric motor, and the battery system. The system integrates two inverters, a bidirectional DC–DC converter, motor winding, and an RSO-based control unit to enhance charging performance as shown in the fig.1. The topology is optimized for compactness and high efficiency

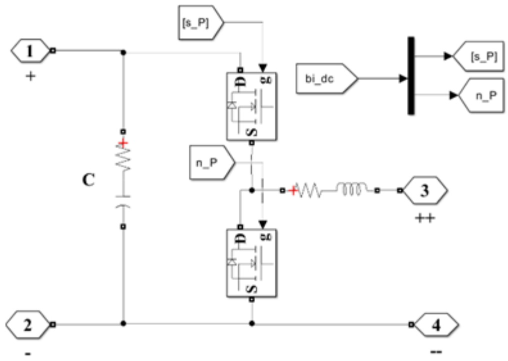
A. DC Source and Bidirectional DC–DC Converter

The system is supplied by a regulated DC voltage source, representative of the output from a rectified grid interface or a standalone DC charging station [12]. This source is responsible for maintaining a stable input to the power conversion chain under both charging and regenerative modes. The voltage level is chosen based on the required operating range of the converter and battery, and it must remain within defined limits to support dynamic load variations during electric vehicle operation. The simulation models of the DC source and bidirectional converters are presented in the figure.2

To facilitate bidirectional energy flow, a DC–DC converter is connected between the DC source and the internal traction and battery subsystems [7-8]. This converter is designed to operate in both buck and boost configurations, depending on the direction of power transfer. In buck mode, the converter steps down the voltage during battery charging, supplying a controlled current based on the battery's charging profile [9] [10]. The converter topology comprises high-speed switching devices, inductors, and filtering elements. Its design ensures high power conversion efficiency and reduced ripple characteristics. The mode of operation is selected based on voltage sensing and directional energy demands, ensuring seamless transition between driving and charging states [11].



(a)



(b)

Figure.2 Simulation models a) DC source and b) Bidirectional converter

B. Modelling of Inverter-1 and Motor Winding

The first inverter, labelled Inverter-1, is placed between the bidirectional DC–DC converter and the motor winding. The simulation model of inverter-1 is displayed in fig.3. Its primary function is to perform real-time DC–AC conversion to generate a balanced three-phase waveform required to drive the motor [13]. During traction mode, Inverter-1 synthesizes sinusoidal AC signals that energize the stator windings, producing a rotating magnetic field to generate mechanical torque. The generated waveform is synchronized to motor speed and load torque, ensuring optimal torque-per-ampere utilization and efficient operation across varying speeds.

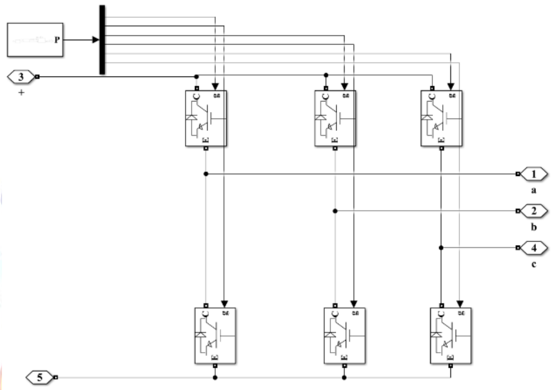


Figure.3 simulation model of the inverter-1

This inverter supports four-quadrant operation by dynamically adjusting the amplitude and phase angle of the output waveform, allowing for forward and reverse motion as well as motoring and braking modes. It responds to electrical reference inputs—such as speed demand or torque feedback-and modulates its switching devices accordingly using techniques such as space vector modulation (SVM) or sinusoidal PWM [14-15]. The output waveform must be precisely shaped to reduce current distortion and electromagnetic interference, both of which directly affect the performance of the motor and other downstream electronics. During regenerative braking, the mechanical energy of the rotating machine is converted back into electrical energy. In this mode, the motor functions as a generator, producing three-phase AC voltage at its terminals. Inverter-1 operates in reverse conduction mode, converting this AC back into DC and routing it upstream to the DC link. This recovered energy can either be transferred to the battery through Inverter-2 or sent to the DC source through the bidirectional converter, depending on system mode and energy flow configuration. The motor winding acts not only as the active component for propulsion but also serves as a passive inductive filter in charging or braking scenarios. When used as an inductor, the motor smoothens high-frequency current components generated by the inverters, suppressing harmonics and improving the quality of power delivered to the battery or sourced from it. This dual-use of the motor winding eliminates the need for dedicated filter inductors, contributing to system compactness and weight reduction, which are critical in vehicle-integrated applications [16] [17].

C. Modelling of Inverter 2 and Battery

The second inverter, referred to as Inverter-2, is connected between the motor winding and the battery system. Its purpose is to regulate the energy flow between the motor and the battery under both charging and discharging conditions, the simulation model of the battery is shown in the figure.4. Unlike Inverter-1, which primarily manages traction control, Inverter-2 is dedicated to power conditioning for the battery, performing AC–DC and DC–AC conversion as required based on the operational state of the system.

During regenerative braking, when the motor acts as a generator and delivers three-phase AC power, Inverter-2 operates as a rectifier. It converts the incoming AC waveform into a regulated DC output suitable for battery charging. This DC power is filtered and shaped to ensure it aligns with the battery's voltage and current acceptance profile. The inverter's operation in this mode supports controlled energy recovery, allowing kinetic energy from braking to be effectively captured and stored in the battery, improving the overall energy efficiency of the system. In discharge mode, when the battery is required to supply energy, Inverter-2 reverses its role and functions as a DC–AC converter [18-19].

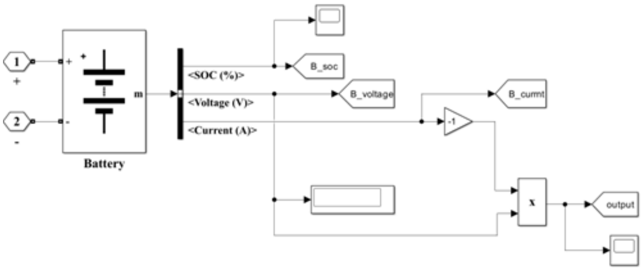


Figure.4 Simulation model of the battery

The battery itself is interfaced with voltage, current, and thermal sensors to enable real-time monitoring of its State of Charge (SOC), health, and operating limits [20]. Charging and discharging are managed within safe thresholds to prevent overvoltage, overcurrent, or thermal stress. The output of Inverter-2 is regulated to maintain consistent power quality and protect the battery management system (BMS) from transient disturbances or harmonic distortion.

3. CONTROL TOPOLOGY

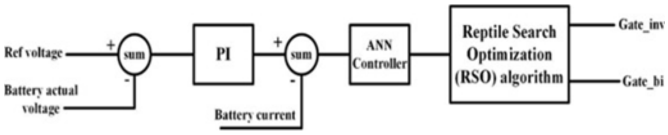


Figure.5 Controlling topology

The control topology of the proposed system integrates both conventional and intelligent control techniques to ensure effective power regulation, voltage tracking, and current control within the bidirectional converter-based charging system. The architecture, as shown in Fig.5, is composed of three main stages: a PI controller, an Artificial Neural Network (ANN) controller, and the RSO algorithm, working in coordination to generate optimized gating signals for both the inverter (Gate_inv) and bidirectional converter (Gate_bi). The output from the ANN is directed to the RSO algorithm block, which acts as the final decision-making unit. The RSO block continuously evaluates system parameters and applies its bio-inspired search mechanism to optimize the PWM switching pulses for both the inverter and bidirectional converter. It determines the most efficient gating patterns to minimize harmonic distortion, switching loss, and overshoot while maintaining accurate voltage and current regulation.

The coordinated action of the PI, ANN, and RSO components allows the system to transition smoothly between different load conditions and operating modes such as charging, discharging, and regenerative braking. The control structure ensures that the gate signals (Gate_inv and Gate_bi) are generated with high precision, resulting in improved converter efficiency, waveform quality, and battery protection. This multi-layered control strategy effectively combines the simplicity of classical control, the learning capability of ANN, and the global optimization strength of RSO.

4. PROPOSED METHOD

The control optimization in the proposed system is achieved using the RSO algorithm, a bio-inspired metaheuristic technique modelled on the intelligent and cooperative hunting behaviour of crocodiles. In nature, crocodiles utilize strategic group coordination, encircling manoeuvres, and adaptive strike patterns to trap prey.

Unlike traditional optimization techniques such as Improved Particle Swarm Optimization (IPSO) or Neural Network–PSO (ANN–PSO) hybrids, RSO does not rely on large-scale training datasets, prior knowledge, or manually tuned weights. It eliminates the complexity of learning models while offering faster convergence in nonlinear, multidimensional search spaces. The algorithm begins by initializing a set of candidate solutions (agents) randomly within the control parameter boundaries. These agents then iteratively update their positions using adaptive movement equations inspired by real reptile strategies, including encircling, attacking, and following group leaders. A fitness function, defined in terms of error minimization (voltage, current, SOC), harmonic distortion, and power loss, guides this movement. The continuous switching between exploration and exploitation phases allows RSO to escape local optima and achieve a stable global minimum in fewer iterations. This real-time capability makes RSO highly suitable for embedded applications in electric vehicles, where fast, adaptive control decisions are critical for energy efficiency, battery health, and system safety.

In the proposed system, RSO receives real-time feedback inputs such as:

- Reference battery charging current
- Measured DC-link voltage and current
- Error between desired and actual output voltage or SOC
- Inverter current/voltage conditions during both charging and regeneration

The objective function of the RSO controller is formulated to minimize:

- Voltage and current error (tracking performance)
- Switching and conduction losses
- Total Harmonic Distortion (THD)
- Ripple in output waveform
- Battery stress during charge/discharge cycles

Mathematically, the fitness function FFF to be minimized is expressed as:

$$F = w_1.\left|V_{ref} - V_{out}\right| + w_2.THD + w_3.P_{loss} + w_4.\Delta SOC \ldots\ldots.. (1)$$

Where w_1,w_2,w_3,w_4 are adaptive weights assigned to prioritize objectives under dynamic operating conditions:

RSO iteratively updates the position of each virtual agent (solution candidate) in the search space using adaptive encircling and hunting equations. After a defined number of iterations, the optimal switching parameters are selected and used to generate the final PWM signals for both the bidirectional converter and inverters.

The integration of RSO into the control scheme brings the following advantages:

- Faster convergence compared to IPSO under dynamic loading
- Reduced ripple and improved waveform quality
- Lower computational overhead as it does not require offline training like neural networks
- Real-time adaptability to load changes and energy flow direction
- Minimized stress on the battery, extending lifecycle and safety margins

Simulation results demonstrate that the RSO-integrated control system achieves faster voltage regulation, lower steady-state error, and improved dynamic performance compared to the IPSO-based counterpart. Across multiple test scenarios-such as sudden load variations, SOC-based charging profiles, and regenerative transitions-RSO exhibits superior adaptability and robustness. The ripple content in the output waveforms is significantly reduced, and switching losses are minimized due to more stable duty cycle convergence. Additionally, the battery is charged more efficiently, with tighter control over the charging current and fewer oscillations, contributing to longer battery life and safer operation.

5. SIMULATION RESULTS AND DISCUSSION

IPSO-BASED RESULTS

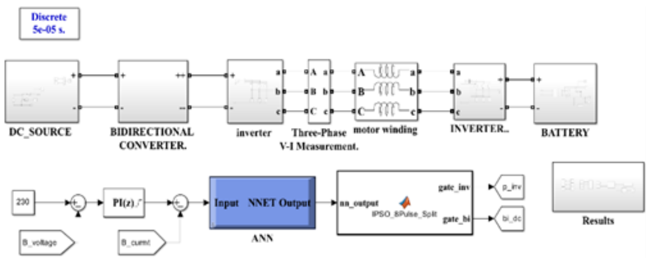


Figure.6 Simulink model for the ANN–IPSO controller

This Simulink model appears to represent a bidirectional power flow system between a DC source and a battery via an inverter and motor drive setup. The control system uses an ANN tuned by the IPSO algorithm for control, likely in managing bidirectional energy transfer and motor control.

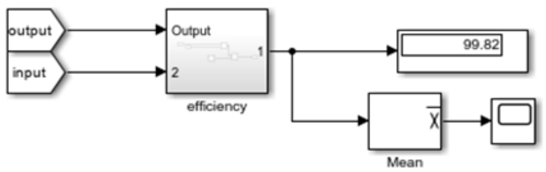


Figure.7 Efficiency by using IPSO

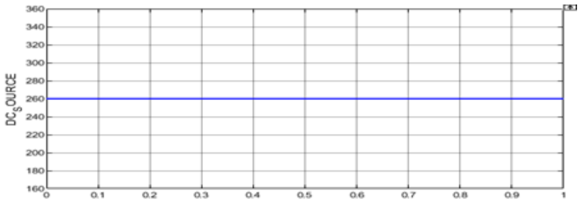
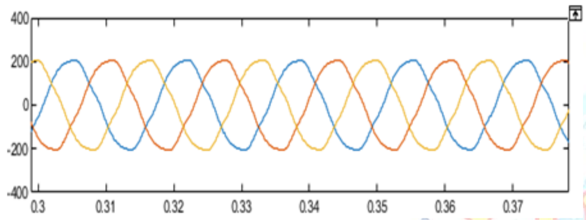
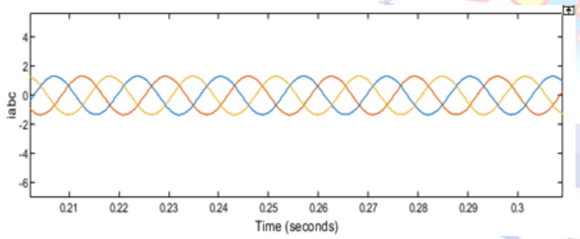


Figure.8 Output of DC source



(a)



(b)

Figure.9 Three phase inverter a) voltage and b) current

The inverter-side output voltages exhibit a balanced three-phase waveform, confirming correct inverter operation. Each phase maintains a consistent amplitude centered on the DC bus voltage, producing a clean sinusoidal output. The current waveforms display symmetry, with consistent amplitude and minimal distortion.

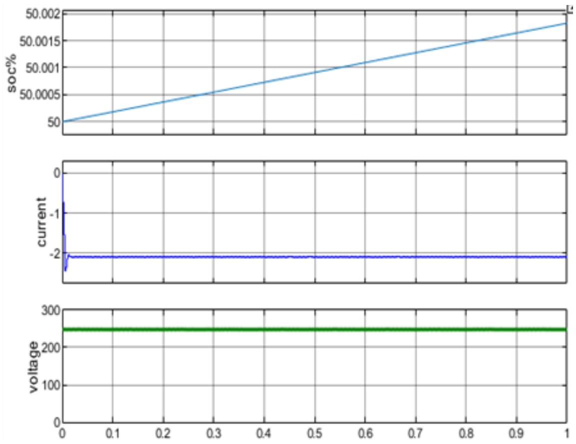


Figure.10 Battery related soc, voltage, and current

The battery is in charging mode, starting at 50% SOC and increasing slightly to 50.002%, indicating charging. The current remains stable at around -2.1 A, confirming controlled charging. The voltage is constant at approximately 265 V, showing effective voltage regulation. Overall, the system ensures stable and efficient charging under the control of the ANN–IPSO controller.

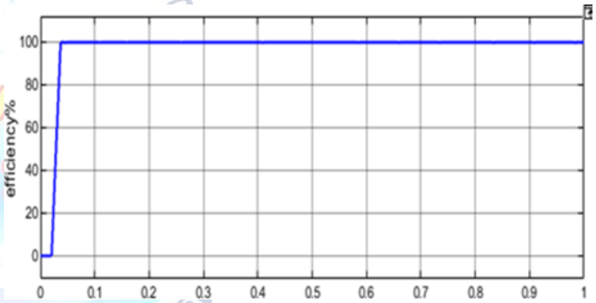


Figure.11 waveform of Efficiency %

Fig.11 displays the overall efficiency (η) from DC source to battery

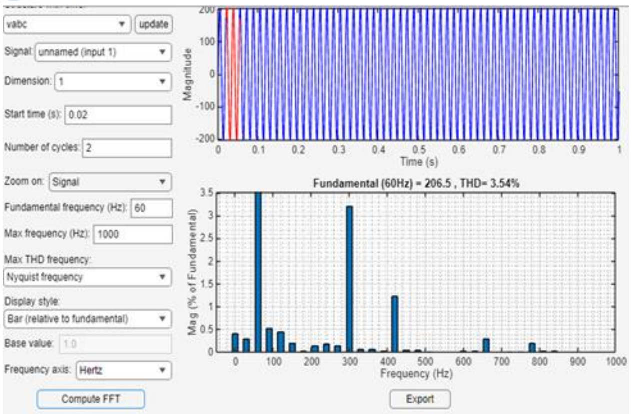


Figure.12 Thd value of inverter side voltage

The inverter-side voltage exhibits a THD of 3.54%, indicating a high-quality sinusoidal output. This THD level falls well within the acceptable limits for motor drive applications, which typically require THD values below 5%. The low distortion reflects the effectiveness of the ANN–IPSO-based controller in managing switching operations, resulting in smooth voltage waveforms, minimized harmonic losses, and improved overall system efficiency.

RSO-Based Simulation Results

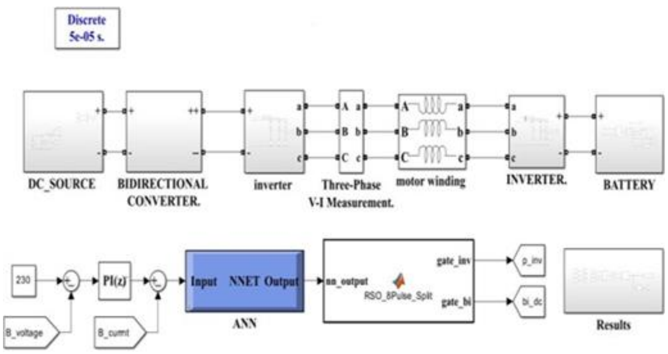


Figure.13 Schematic diagram of Reptile Search Optimization of model

This Simulink model of fig.13 represents a bidirectional power flow system between a DC source and a battery through an inverter and motor drive, specifically designed for on-board battery charging in PHEVs. An ANN controller is employed to regulate energy transfer and manage motor control. To optimize the performance of the ANN, the model utilizes RSO, which offers faster convergence and improved handling of nonlinearities in dynamic environments. Standard drive cycles and charging data are incorporated to simulate real-world conditions, ensuring accurate and efficient control during both charging operations.

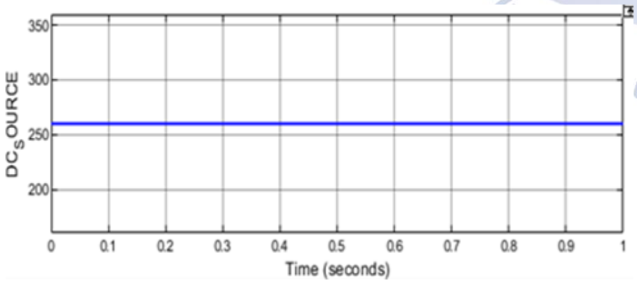
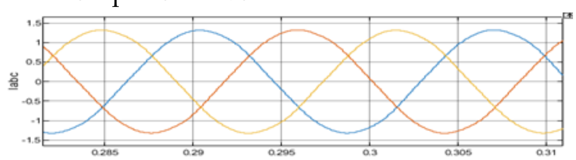
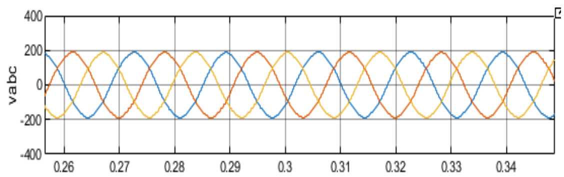


Figure.14 output of Dc source



(a)



(b)

Figure.15 Three-phase inverter a) voltage and b) current

The inverter-side phase currents are balanced and sinusoidal, indicating effective current control and uniform load sharing across all three phases. Each current waveform exhibits symmetry and consistent amplitude, demonstrating the effectiveness of the Neural Network controller enhanced through RSO. The integration of RSO significantly improves the controller's performance, resulting in reduced harmonic distortion and enhanced overall system efficiency.

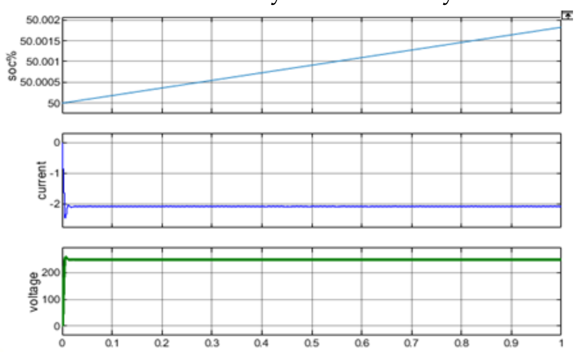
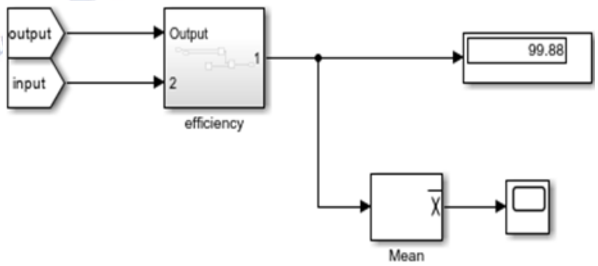
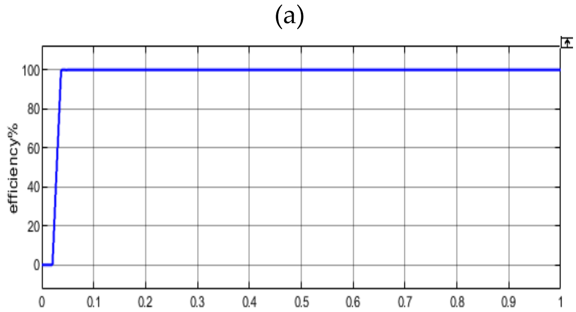


Figure.16 Battery soc, current and voltage

The battery operates in charging mode, beginning at a 50% state of charge (SOC) and increasing slightly to 50.002%, indicating a slow and controlled charging process. The charging current remains stable at approximately -2.1 A, confirming consistent and regulated power flow. The battery voltage is maintained at around 265 V, demonstrating effective voltage regulation. Overall, the system achieves stable and efficient charging performance under the control of the ANN optimized by RSO.



(a)



(b)

Figure. 17 (a) and (b) Showing the efficiency of the system

The overall efficiency (η) from the DC source to the battery is high and shows a slight improvement due to the implementation of RSO.

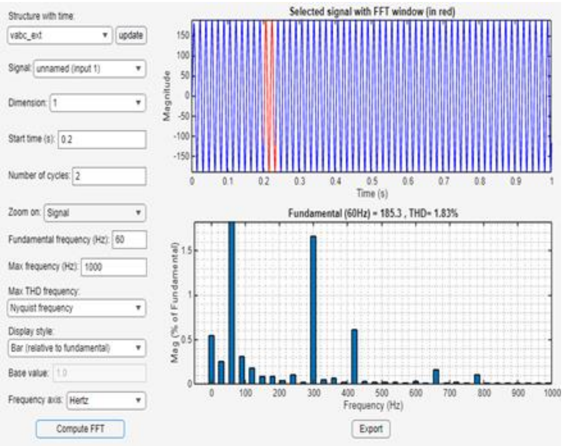


Figure.18 Thd value of Vabc

The inverter-side voltage exhibits a THD of 1.83%, indicating a high-quality sinusoidal output suitable for sensitive motor drive applications. This THD level is well below the standard threshold of 5%, as recommended by IEEE 519, ensuring compliance with power quality standards. The low distortion demonstrates the effectiveness of the ANN controller optimized using RSO, which ensures precise switching control. This results in smooth voltage waveforms, reduced harmonic losses, and enhanced overall system efficiency and reliability, making it ideal for PHEV operations.

Table-I THDs comparison table

Performance Parameter	IPSO-Based Control	RSO-Based Control
THD of Vabc	3.54%	1.83%

From the simulation outcomes, it is evident that the RSO-based control strategy offers a substantial improvement in output waveform quality. The THD of the inverter-side voltage is reduced from 3.54% (IPSO) to 1.83% (RSO), demonstrating a notable suppression of harmonic distortion. This is attributed to RSO's adaptive switching logic and smooth duty cycle regulation, which leads to more symmetrical and stable output voltages. Additionally, the RSO system shows reduced ripple amplitude, improved tracking accuracy, and less overshoot in the voltage waveform when compared to the IPSO method.

6. CONCLUSION

This paper presented a novel RSO-based hybrid control strategy for a bidirectional converter integrated with a dual-inverter system for on-board battery charging in PHEVs. The system architecture efficiently reused existing motor windings as inductive filters and leveraged both inverter stages for dynamic power routing between the grid, motor, and battery. By replacing the conventional IPSO-based controller with the RSO algorithm, the proposed method introduced an adaptive and computation-efficient control framework capable of handling nonlinearities and mode transitions without neural network dependencies. Simulation results validated that the RSO-integrated system achieved lower THD, faster convergence, and reduced voltage ripple compared to the IPSO-based system. Specifically, inverter-side THD was reduced from 3.54% to 1.83%, demonstrating a significant improvement in waveform quality. The RSO controller also offered real-time flexibility, stable performance under varying load conditions, and reduced control overhead.

Conflict of interest statement

Authors declare that they do not have any conflict of interest.

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